AFRL-ML-TY-TP-2001-0033

Comparison of Time-Averaged Concentrations Measured at Fixed Locations and Painters' Breathing Zones During Aircraft Spray Painting in Conditions of Straight-Through and Recirculating Ventilation

Joseph D. Wander
Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

William B. Belser, Stacie M. Griffie and Mark H. Smith
75 MDG/SGPB
7238 6th Street, Building 249
Hill AFB, UT 84056

Glenn R. Palmer
OO-ALC/EMC
7274 Wardleigh Road
Hill AFB, UT 84056-5137

AIR FORCE RESEARCH LABORATORY
MATERIALS & MANUFACTURING DIRECTORATE
AIR EXPEDITIONARY FORCES TECHNOLOGIES DIVISION
139 BARNES DRIVE, STE 2

NOTICES

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE US GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

THIS TECHNICAL PAPER HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION. ORIGINALLY PRESENTED TO THE 94th ANNUAL MEETING AND EXHIBITION, AIR & WASTE MANAGEMENT ASSOCIATION, ORLANDO, FLORIDA, 26 JUNE 2001. *PROCEEDINGS OF THE AIR & WASTE MANAGEMENT ASSOCIATION'S 94th ANNUAL CONFERENCE & EXHIBITION* IS AVAILABLE AS A CD-ROM FROM WWW.AWMA.ORG

JOSEPH D. WANDER, Ph.D
Program Manager

Lynn L. Borland

LYNN L. BORLAND, Major, USAF, BSC
Chief, Weapons Systems Logistics Branch

Donald R. Huckle, Jr.

DONALD R. HUCKLE, JR., Lt Col, USAF
Chief, Air Expeditionary Forces Technologies Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	26 June 2001	Meeting abstract / 990901-010531

4. TITLE AND SUBTITLE Comparison of Time-Averaged Concentrations Measured at Fixed Locations and Painters' Breathing Zones During Aircraft Spray Painting in Conditions of Straight-Through and Recirculating Ventilation

5. FUNDING NUMBERS
Contract No: F11623-94-C-0024/RL43
JON: 2103A36B

PE: 63723F

6. AUTHORS Joseph D. Wander, William B. Belser, Mark H. Smith, and Glenn R. Palmer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Parsons Engineering Sciences
South Jordan, Utah

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/MLQL
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-ML-TY-TP-2001-0033

11. SUPPLEMENTARY NOTES
Technical monitor: Dr Joe Wander, AFRL/MLQL, 850-283-6240 [DSN 523-6240]
Presented 010626, in *Proceedings 94rd Annual Conference, Air & Waste Management Association*, Orlando

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Distribution unlimited.	A

13. ABSTRACT *(Maximum 200 words)*

Routine Industrial Hygiene exposure sampling was conducted during application of prime and top coats to C-130 aircraft in a ventilated insert located in Building 270, Hill Air Force Base. Equivalent sets of measurements were taken by staff of the Bioenvironmental Engineering office for each of three aircraft, one of which was painted under conditions of 80% recirculation of filtered painting exhaust air. Typically large scatter was evident both within and among the data sets so generated, but the set of exposure measurements taken in the recirculated environment was not significantly elevated relative to the two sets measured in staright-through conditions. Toxicants measured were butyl acetate, diisobutyl ketone, ethylbenzene, methyl amyl ketone, methyl propyl ketone, xylene, hexamethylene diisocyanate (HDI), toluene 2,4-diisocyanate (TDI), and strontium chromate.

Transcription errors have been corrected in Figure 2.

14. SUBJECT TERMS	15. NUMBER OF PAGES
solvent, spray painting, recirculation, ventilation, exposure, air toxic	12
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500 Computer Generated STANDARD FORM 298 (Rev 2-89)
Prescribed by ANSI Std 239-18
298-102

Comparison of Time-Averaged Concentrations Measured at Fixed Locations and Painters' Breathing Zones during Aircraft Spray Painting in Conditions of Straight-Through and Recirculating Ventilation

Paper #711

Joseph D. Wander
AFRL/MLQL, 139 Barnes Drive, Suite 2, Tyndall AFB, Florida 32403-5323

William B. Belser, Stacie M. Griffie and Mark H. Smith
75 MDG/SGPB, 7238 6th St. Bldg. 249, Hill AFB, Utah 84056

Glenn R. Palmer
OO-ALC/EMC, 7274 Wardleigh Road, Hill AFB, Utah 84056-5137

ABSTRACT

As part of an extensive upgrade to the ventilation system of the aircraft painting insert located inside Building 270 at Hill Air Force Base, the ducting was configured to allow recirculation of as much as 80% of the air passing through the exhaust filters. This was designed to enable a strategy to decrease heating costs for the facility and to concentrate the exhaust stream for later application of VOC emission controls if needed.

Identical [within the limits of experimental and behavioral repeatability] sets of time-averaged measurements were made during painting of C-130 aircraft under conditions of 0% [straight-through ventilation] and 80% recirculation. These include measurements of individual VOCs known to be emitted during spray application of paint, chromate, and two diisocyanates. Data were collected using both samplers on stands at fixed positions and samplers attached to personnel applying paint.

No characteristic differences were observed among the three sets of measurements, consistent with predictions from simple process models of this recirculated facility. Such predictions are a necessary element of the detailed risk–benefit analysis that should guide any decision to apply exhaust recirculation in candidate facilities. As configured, the insert was seen to be unsuitable for recirculation because contaminants in the recirculated stream escape through openings at the rear of the structure.

INTRODUCTION

Recirculation of a portion of the air used to ventilate an aircraft painting enclosure is a two-pronged pollution prevention tool. First, it recovers the same portion of energy used to adjust temperature or humidity of air brought into the ventilation system. Ogden Air Logistics Center is

an aircraft maintenance depot located on Hill Air Force Base (HAFB), in high desert terrain in northern Utah, ~300 miles ESE of Mountain Home AFB (MHAFB). HAFB and MHAFB experience similar environmental conditions, so the annual heating requirement of ~5000 degree-days documented[1] for MHAFB also applies to HAFB. And, as calculated[1] for MHAFB, using recirculation in its aircraft painting operations could decrease HAFB's energy costs by $~40K and its CO_2 emission rate by half a ton annually.
HAFB is located in an ozone-maintenance area, and it is listed as a major source of emissions by the Utah Division of Air Quality. Proximity to Salt Lake City, a number of large oil refineries, and the Great Salt Lake are all factors that amplify the contribution of HAFB's organic emissions to regional ozone concentrations. The second benefit of recirculation—decreasing the volume of air exiting the ventilation system by increasing the concentration of solvent vapors inside both the workplace and the ducting—improves the option to apply an emission control device, which would lower (by 80% or more) net emissions from painting operations. Smaller control systems are cheaper to install and operate. An operational plus from applying a control is that one may use low-solids coatings, which are optimized for performance, and remain in compliance with the National Emission Standard for Hazardous Air Pollutants applicable to aerospace coating operations.

Despite an earlier technical report[2] that addresses regulatory issues and includes basic design recommendations and operating procedures, the Air Force has been slow to implement recirculation in its large painting facilities. At issue is the fact that recirculation deliberately increases the exposure risk of personnel in the workplace. Despite modeled results that predict[3–6] that the increase is ~1%—much less than the uncertainty in the methods that measure personnel exposure—the absence of comparative data has been a stumbling block to the adoption of this technology. This paper describes such a set of comparative measurements.

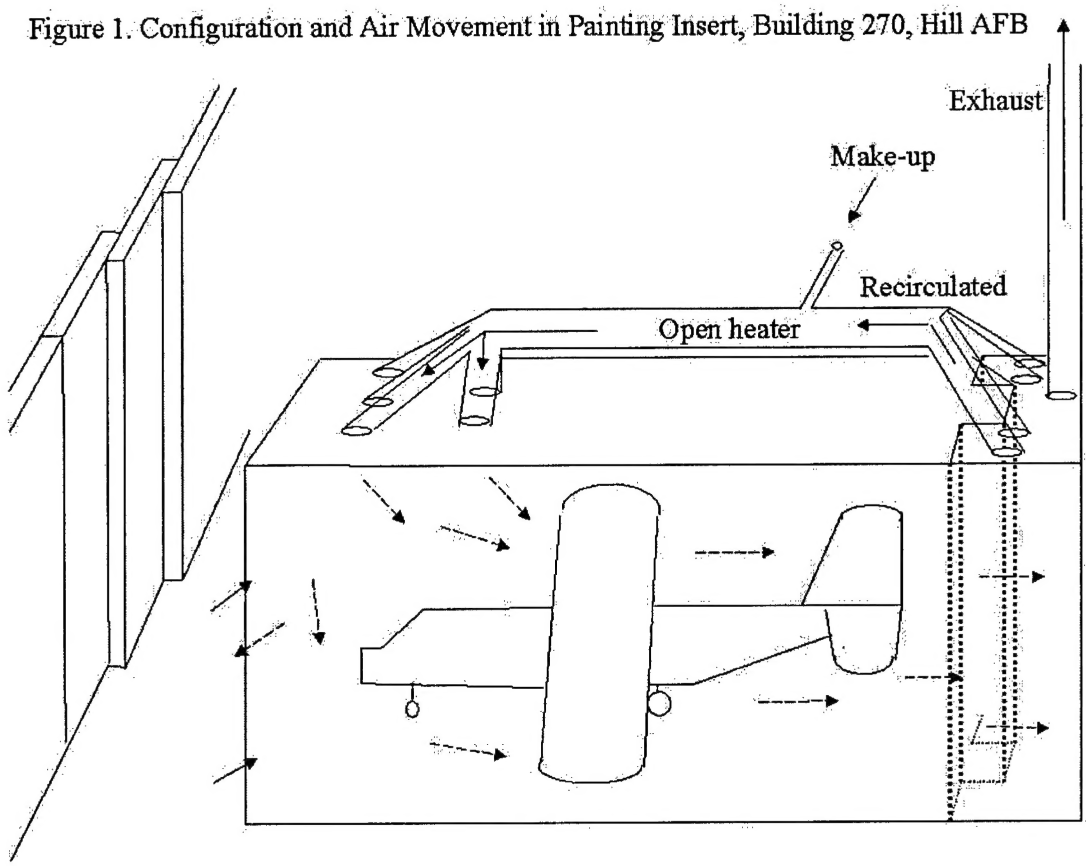
The Aircraft-Painting Facility

Building 270 is a large maintenance hangar, in which a salvaged painting insert is installed on tiers of concrete block to exactly accommodate C-130 aircraft for preparation and painting. This minimum cross section requires 360 kcfm airflow to provide an average linear velocity of 100 ft/min across the enclosed area. Ventilation air from the painting operations exhausts through the ceiling of the building. Some fresh air infiltrates through curtains covering a gap (only the gap is shown in Figure 1) of about 10 feet between the open face of the insert and the exterior hangar doors. The ventilation system delivers air from a number of vents in the ceiling in the rear half of the insert. Except at the extreme rear of the aircraft [near the open face], regions of intense turbulence have been tuned out by adjusting the output through the vents. To minimize exfiltration of overspray and solvent vapors into the rest of the hangar, the system is maintained at negative pressure by removing exhaust air slightly faster than ventilation air is delivered through the vents.

During 1997–1999 the ventilation system was upgraded. A facility demonstration project was undertaken concurrently to install 80% recirculating ventilation and attach a volatile organic compound (VOC)-destruction system. The goal was to validate that these two technologies would combine to save the base approximately $50K in fuel, half a ton of CO_2 emissions, and 10 tons of VOC emissions annually from C-130 painting operations. If the painting workload were to increase, these technologies would allow the base to absorb the additional airborne contaminants with minimal effect on conformity with the Title V permit conditions.

Cuts to the environmental R&D program eliminated the VOC control system, but the recirculating ventilation feature was included in the ventilation system upgrade. Principal elements in the final configuration of the ventilation system are sketched in Figure 1. The enclosure is 180 feet wide, 20 feet high, and 90 feet from the opening to the center bank of filters. An exhaust and several recirculating blowers draw spent air through the filters and deliver it to the exhaust and recirculating ducts, respectively. The ventilation blowers draw make-up air into the recirculating stream, and draw the mixture through a gas flame before delivering it through ducts in the ceiling. Aircraft enter nose first through the hangar doors. Turnaround averages nine days to paint a C-130 from the skin out, including one intensive day of painting.

Figure 1. Configuration and Air Movement in Painting Insert, Building 270, Hill AFB



during which the first shift applies the prime coat and the night and swing shifts apply the top coat in two layers. Cure time between coats is 5–6 hours

The painting process is typically performed during three consecutive shifts by three or four teams of two—a painter and an aide who provides constant logistical support, principally keeping hoses free of obstruction—during the first few hours of each shift. All personnel in the work area are required to wear Tyvek™ coveralls, boots and gloves, and a hood that includes a respirator to which air is supplied through a hose. The respiratory protection factor (RPF) for this hood is 25—*i.e.*, when it is properly fitted and worn a painter in an environment containing 100 ppm of a toxicant will experience only 4 ppm inside the hood. Separate air systems supply breathing air and air to high-volume, low-pressure (HVLP) paint guns, and both are independently isolated from facility ventilation.

AREA AND EXPOSURE MEASUREMENTS

Personnel from 75 MDG/SGPB conducted air sampling on C-130 aircraft painters performing primer and topcoat application on three occasions during calendar years 1999 and 2000. Each of these sampling exercises gathered data both during application of primer and during application of topcoats. Three or four workers performing routine tasks comprised the subjects for each sampling event. Area samples were also collected during some events. One of the three sampling events was conducted while a mixture containing 80% recirculated exhaust was supplied as the ventilation source to the workspace. The other two events were conducted under standard operating conditions. Although it is impossible to exactly reproduce conditions between such sampling events, the three sampling exercises were—except for the mode of ventilation and precise composition of the coating materials—conducted under equivalent conditions.

Methods

Cartridges filled with absorptive or adsorptive media specific for the particular analytes of interest were attached inside the hood of personnel immediately before they began routine painting tasks. A few were also placed at fixed locations in the immediate workspace. Each cartridge was fitted to a constant-velocity air pump, which drew a small volume of air from the space immediately outside the breathing zone of the wearer (or from the work area). When particularly large exposures were considered a possibility, pairs of cartridges were connected in series to ensure against saturation of the forward sampler. At the conclusion of the collection period the sampling cartridges were sealed, positively identified, and shipped for analysis.

Standard analytical methods used are identified in Table 1. The results are reported as amounts of the analyte. Particle size[2] was not considered in chromium or isocyanate determinations, so respiratory exposure may be overestimated. The running time of the pump was used to calculate the total volume of air sampled, from which the 8-hour time-weighted averages reported in Table 2 were calculated. The full set of individual values will be issued as an AFRL technical report.

Table 1. Methods Used and Sources of Analyses

Toxic Contaminant	Abbreviation	Standard Method	Analyses Performed by
n-Butyl Acetate	*n*BA	NIOSH 1450	OSHA Salt Lake Technical Center
Diisobutyl Ketone	DIBK	NIOSH 1300	
2-Pentanone	MPK		
Ethylbenzene	EtB	OSHA 1002	
Xylene	Xyl		
Methyl *n*-Amyl Ketone	MAK	NIOSH 1301	
Total Chromate	Cr^{+6}	OSHA ID 215	
Hexamethylene Diisocyanate	HDI	OSHA 42	
Toluene 2,4-Diisocyanate	TDI		

RESULTS

Results from three sampling events are presented in Table 2. The TLV (threshold limit value) for a constituent is a concentration estimated by the American Council of Government Industrial Hygienists to be tolerable as an 8-hour time-weighted average five days per week for 40 years. It is almost always equal to the permissible exposure limit (PEL), which is an enforceable standard for occupational exposures, as defined in 29 CFR 1910.1000. The lower of the TLV or PEL is the maximum value allowed in Air Force

Table 2. Summary of Constituents Measured in Painting Facility, Building 270 Hill AFB

Constituent	TLV	Measured 8-Hour TWAs (same units as TLV)	Coat	Percent Recirc	Data Set
n-Butyl Acetate (NBA)	150 ppm	0.90; 0.98; 1.03; 0.19	Top	80	1
		1.05 (avg)		0	3
		ND; ND; ND; ND	Prime		3
		0.21; 1.09; 1.16; 1.74			2
Diisobutyl Ketone (DIBK)	25 ppm	0.39; 0.46; 0.57; 0.58; 0.66	Prime	80	1
		0.08; 0.16; 0.21; 0.22		0	2
		ND; 0.08; 0.15; 0.24			3
Ethylbenzene (EtB)	100 ppm	0.03; 0.03; 0.03; 0.04	Top	80	1
		ND; 0.03; 0.03; 0.04		0	2
		0.02 (avg)			3
		ND; ND; ND; 0.05¶	Prime		3
Hexamethylene Diisocyanate (HDI)	0.034 mg/m^3	0.003; 0.004; 0.021; 0.022	Top	80	1
		0.009; 0.020; 0.025; 0.036		0	2
		0.022 (avg)			3
Methyl *n*-Amyl Ketone (MAK, 2-Heptanone)	50 ppm	1.80; 1.97; 2.11; 2.46	Top	80	1
		0.48; 1.75; 2.04; 2.23		0	2
		ND; ND; 0.14; 0.52			3
Methyl *n*-Propyl Ketone (2-Pentanone)	200 ppm	0.16; 0.17; 0.21; 0.23; 0.24	Prime	80	1
		0.03; 0.08; 0.09; 0.09		0	2
		ND; ND; ND; 0.10			3
Strontium Chromate	0.01 mg/m^3	0.143; 0.144; 0.172; 0.221; 0.354	Prime	80	1
		0.040; 0.098; 0.122; 0.158		0	2
		0.000; 0.023; 0.055; 0.083			3
Toluene 2,4-Diisocyanate (TDI)	0.036 mg/m^3	0.086; 0.111; 0.178; 0.185	Top	80	1
		0.415; 0.537; 0.515; 0.645		0	2
		0.528 (avg)			3
Xylene (Xyl)	100 ppm	0.38; 0.40; 0.49; 0.53; 0.58	Prime	80	1
		0.08; 0.22; 0.24; 0.25		0	2
		ND; ND; ND; 0.03			3
		0.30; 0.30; 0.35; 0.39	Top	80	1
		ND; 0.07; 0.07; 0.08		0	2
		0.056 (avg)			3

¶ Ethylbenzene is not a constituent of the primers used.

operations, and concentrations exceeding 0.5 of that maximum value (the *action level*) trigger careful scrutiny of the circumstances causing the high concentration.

Several features stand out in Table 2. Of 99 VOC determinations, all can positively be said to be less than the action levels. All five concentrations of strontium chromate measured during recirculation exceed the action level compared to two of eight measurements taken in standard ventilation mode, and the average values are twice and four times those of the respective standard ventilation sets. However, the PEL for chromates is so small that overexposure is presumed whenever it is used. Exactly the opposite was observed for isocyanates—Among TDI measurements, none taken during recirculation reached the action level, while at least five of eight taken in standard ventilation mode exceed it. And the average values for HDI and TDI under recirculating conditions are one-third and one-fourth, respectively, of the average concentrations measured under standard ventilation conditions.

DISCUSSION

Summaries of comparisons within categories in Table 2 are presented in three tables below. Although the array of data in Table 2 is not large enough to support a detailed statistical analysis, it is sufficient to support a critical examination. The hypothesis, predicted[1,3–6] from mass balance and dilution calculations, is that recirculation into the large air volumes employed in Building 270 will cause increases in concentrations inside the hangar volume, but that the increases in the vicinity of the painting operation will be undetectably small because they are smaller than the intrinsic uncertainty of the measurements.

Table 3 compares ranges and means of concentrations. Because the ranges appear to be ordinary, let us concentrate on the means, which will simplify the task of comparison and minimize

Table 3. Comparison of Ranges and Averages of Concentrations

	80 % Recirculation (Set 1)			Straight-Through Ventilation (Sets 2 and 3)					
Name	Min	Ave.	Max	Min 2	Min 3	Ave. 2	Ave. 3	Max 2	Max 3
*n*BA	0.19	0.775	1.03	0.21	<1.05	1.049	1.05;ND	1.74	>1.05
EtB	0.03	0.032	0.04	ND	<0.02	0.025	0.02;.01	0.04	>0.02
MAK	1.80	2.083	2.46	0.48	ND	1.623	0.17	2.23	0.52
Xyl	0.30	0.34	0.39	ND	<0.056	0.056	0.056	0.08	>0.056
DIBK	0.39	0.552	0.66	0.08	ND	0.167	0.12	0.22	0.24
MPK	0.16	0.208	0.24	0.03	ND	0.069	0.025	0.09	0.10
Xyl	0.38	0.494	0.58	0.08	ND	0.20	0.008	0.25	0.03
HDI	0.003	0.008	0.022	0.009	<0.022	0.022	0.022	0.036	>0.022
TDI	0.086	0.140	0.185	0.415	<0.528	0.528	0.528	0.645	>0.528
Cr^{+6}	0.143	0.223	0.354	0.040	0.000	0.105	0.041	0.158	0.083

distortion that would result from single aberrant values. Table 4 compares the ratio of values between pairs of determinations of each constituent measured. Examining signs only, 8/20 means are lower in the recirculation set and 12 are higher. Of these, 6/20 are smaller by more than half

Table 4. Pairwise Comparison of Means of Sets of Measurements							
	Means			Ratio of Pair			
Name	Set 1	Set 2	Set 3	1/2	1/3	2/3	1/[0.5(2+3)]
*n*BA	1.023	1.049	1.05	0.98	0.97	1.00	0.97
EtB	0.032	0.025	0.02	1.28	1.60	1.25	1.42
MAK	2.083	1.623	0.17	1.28	16.00	9.54	2.45
Xyl	0.034	0.056	0.056	0.61	0.61	1.00	0.61
Geometric Mean of Topcoat VOCs				0.99	1.97	1.86	1.20
DIBK	0.552	0.167	0.12	3.31	4.60	1.39	3.85
MPK	0.208	0.069	0.03	3.01	6.93	2.30	4.20
Xyl	0.494	0.199	0.056	2.48	8.82	3.87	3.55
Geometric Mean of Primer VOCs				2.91	6.55	2.31	3.86
HDI	0.008	0.022	0.022	0.36	0.36	1.00	0.36
TDI	0.140	0.528	0.528	0.27	0.27	1.00	0.27
Cr^{+6}	0.223	0.105	0.041	2.12	5.44	2.56	3.05

of the smaller value, and 8/20 are larger by the same proportion. For three of the 10 compounds the ratio between the two standard series is farther from unity than is that of one of the pair to the recirculated value. There is no clear trend of increase or decrease across the data sets.

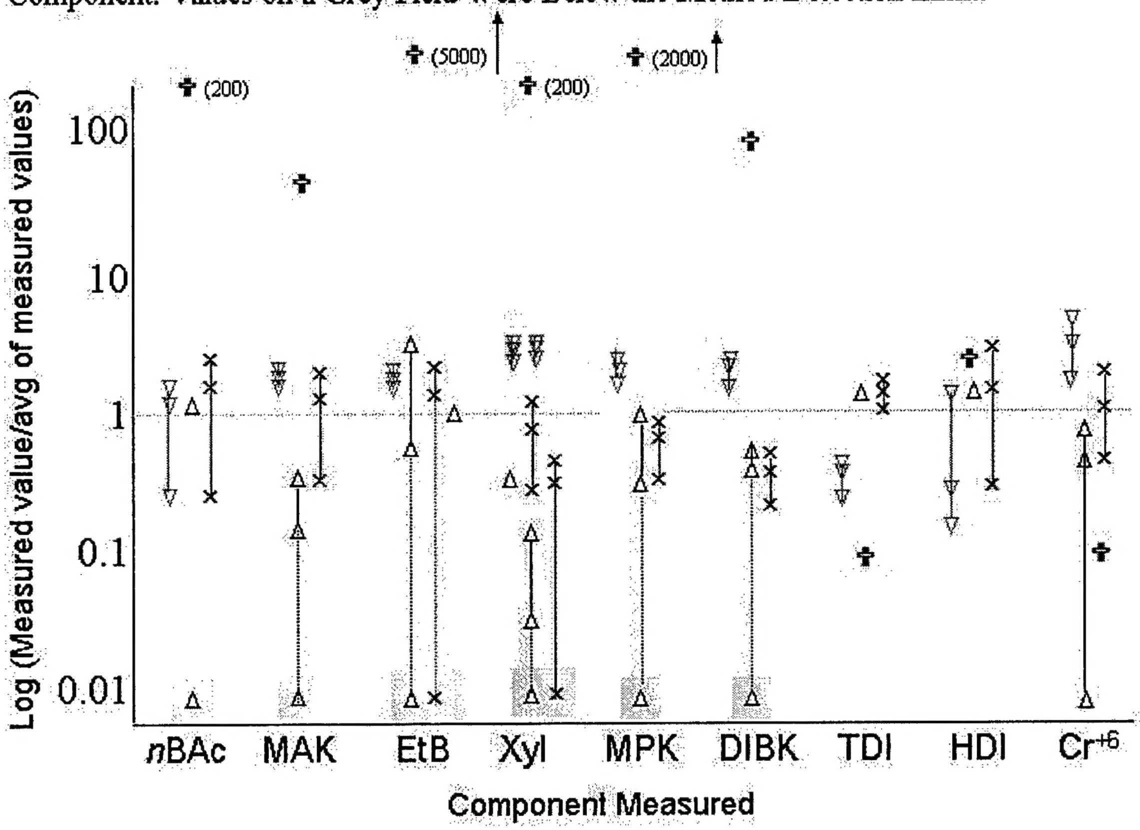
Table 5 directly examines the noise inherent in the measurement system. During a painting session, all of the constituents are delivered in constant relative proportions into identical conditions. Large differences in ratio of concentrations among sets of measurements signal large

Table 5. Comparison of Ratios of Concentrations Among Constituents Applied Concurrently						
Name (Down)/ Name (Across)						
	Set No.	EtB	MAK	Xyl	HDI	TDI
*n*BA	1	38	**0.49**	30	**128**	7
	2	42	**0.65**	19	**48**	5
	3	53	**6**	19	**2**	2
EtB	1		0.02	0.94	4	0.23
	2		0.02	0.44	1	0.05
	3		0.12	0.36	0.91	0.04
MAK	1			**61**	**260**	**15**
	2			**29**	**74**	**3**
	3			**3**	**8**	**0.33**
Xyl	1				4	0.24
	2				3	0.11
	3				3	0.11
HDI	1					0.06
	2					0.04
	3					0.04

uncertainty in the method. Of the 15 pairs of comparisons possible among the six topcoat constituents sampled, six exhibit ranges over a factor larger than 10, reinforcing the implied statement above that all of the changes in concentration are smaller than the noise in the data.

Even allowing for the occasional error, data of this sort are inevitably noisy—because personnel are idiosyncratic, because the orientation and placement of a sampler affect its performance, and because there is uncertainty in the analytical methods. A simpler test of the prediction is to display all three sets of measurements on a common plot (Figure 2). To assemble this plot, the measurements for each constituent were averaged, and each measurement was divided by the average for that component (making the average value 1.0 for all components). A number of measurements less that the method detection limits are shadowed in gray and assigned an arbitrary value of 0.01, and most occurred during one of the priming sessions. It is apparent that all three are "ordinary" sampling events. By design, recirculation increased the average concentrations of these contaminants in this hangar and, as predicted,[3–6] standard methods of sampling and analysis were unable to discriminate the change.

Figure 2. Normalized Plot of Values Measured for Nine Components During Three Sampling Events. ∇ Indicates the Recirculated Series. ✝ Indicates the Threshold Limit Value for Each Component. Values on a Grey Field Were Below the Method Detection Limit.



It is worthy of note that particulate contaminants (isocyanates and chromate) did not increase drastically. We used three-stage paint filters, which are rated to remove 99% of particles from the air stream and which are recommended[2] for all recirculating ventilation systems. The model that predicted that the increases would be lost in data noise also assumed[3,4] 99% capture of particles. As droplets fine enough to pass the filter system are expected[7] to cure fairly rapidly and chromate content of such fines has been shown[8] to be significantly lower than in the bulk paint,

this result is expected. It also suggests that 99% capture is sufficient to maintain acceptable exposure conditions in the working area.

CONCLUSIONS

Although the measurements differed among sampling events, the differences appear to be random and no trends are discriminable. Because only the composition of the ventilation stream is affected by changes to the external ductwork (provided airflow is not increased or decreased), this can be considered a general result. The fractional increase in concentration to which a painter or aide near the area of paint application is exposed while painting at 80% recirculation in a competently designed and maintained large enclosure is minimal.

Several qualifications follow:

- The risk–benefit determination used to evaluate recirculation [or any other engineering decision] must include the global work environment. During the recirculation test, significant effusion of recirculated contaminants produced a detectable odor throughout Building 270. Despite the economic benefit described in the introduction, the inability of the curtains plus forced infusion of make-up air to contain the recirculated contaminants creates an exposure risk to nonpainting personnel. Unless and until engineering changes eliminate this element of exposure risk, routine use of recirculation in the open-ended insert is inappropriate.

- A negligible risk is *not* a zero risk. Some tangible benefit must be projected to support a decision to implement recirculating ventilation in a painting facility.

- Scale has to be considered. The results above apply only to large enclosures, in which dilution is extreme. Concentrations in the recirculated stream will increase as the dimensions of the enclosure decrease, so site-specific modeling is recommended.

- Risk management is a constant process. Failures of maintenance and deviations from safe operating practices amplify exposure risk, effectively invalidating the initial risk–benefit analysis. Employing recirculation implies a contract to preserve the conditions described in the risk analysis.

Finally, the gas-fired stage heating intake air suggests using an in-line device to remove VOCs as part of the recirculating ventilation process. This would lower net concentrations (and exposure risk) or increase the fraction of air that could be recirculated at a given level of risk. The economic benefit would be limited both by diminishing return and mechanical limitations of scale. Enclosures to maintain stealth aircraft might be candidates for extreme compression because they require climate control, and size and power requirements are critical limits for deployment.

REFERENCES

1. Wander, J.D., Adams, B.S., Gibbs, S.T., Williston, C.A. *Proceedings Air & Waste Management Association's 94th Annual Conference and Exhibition* June 2001, Air & Waste Management Association, Orlando, Fla. paper #710.

2. Hughes, S., Ayer, J., Sutay, R. *Demonstration of Split-Flow Ventilation and Recirculation in an Air Force Paint Spray Booth*, Armstrong Laboratory, Tyndall AFB, Florida 1993; AL/EQ-TR-1993-0002 (EPA/600/R-94/214a); p 8.

3. LaPuma, P.T. *Recirculating Industrial Air: The Impact on Air Compliance and Worker's Safety. Case Study: Hill Air Force Base C-130 Painting Operations*, Air Force Research Laboratory, Tyndall AFB, Florida 1998; AFRL-ML-TY-TR-1998-4524.

4. LaPuma, P.T., and Bolch, W.E. *Applied Occupational and Environmental Hygiene* **1999**, *14*, 682–690.

5. LaPuma, P.T. *Applied Occupational and Environmental Hygiene* **2001**, *16*, 1–12.

6. LaPuma, P.T. *Proceedings Air & Waste Management Association's 94th Annual Conference and Exhibition* June 2001, Air & Waste Management Association, Pittsburgh, Pa. paper #3.

7. Morgan, T.J.R. *Chromate Dissociation from Primer Paint in Simulated Lung Fluid*, Air Force Institute of Technology, Wright–Patterson AFB, Ohio 2000; AFIT/GEE/ENV/00M-14; Kauth, D.A. *Dissolution of Chromium from Inhalable Primer Paint Particles into a Simulated Lung Fluid*. Wright–Patterson AFB, Ohio 2001; AFIT/GEE/ENV/01M-07.

8. Fox, J.M. *Chromium Concentration Bias in the Particle Size Distribution of Primer Overspray*, Air Force Institute of Technology, Wright–Patterson AFB, Ohio 2000; AFIT/GEE/ENV/00M-06; Novy, D.B. *Chromate Content Bias as a Function of Particle Size in Aircraft Primer Paint Overspray*. Air Force Institute of Technology, Wright–Patterson AFB Ohio, 2001. AFIT/GEE/ENV/01M-12.

KEYWORDS

Recirculation, VOCs, Strontium Chromate, Chromate, Isocyanate, Risk, Exposure, TLV, Painting